Failure Mechanisms of Fiber Optic Sensors Placed in Composite Materials

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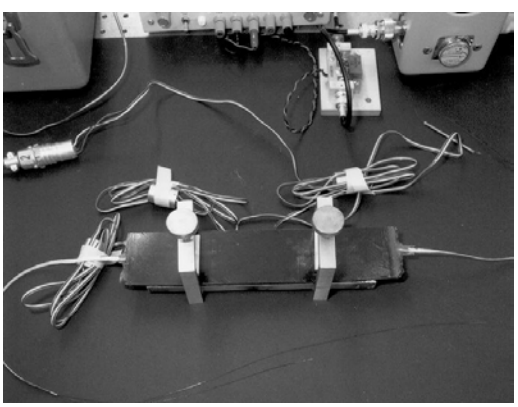
ABSTRACT

This paper provides an overview of considerations associated with placement and operation of fiber optic sensors placed in composite materials. Issues that are discussed include coatings placed on optical fibers and their relationship to the composite structure, orientation of optical fibers in the composite parts, methods of providing strain relief, and terminations. Examples are given associated with a series of examples from aerospace and civil structure applications.

Keywords: fiber optics, composite, grating, sensors

1.0 COATINGS AND PLACEMENT OF FIBER OPTIC SENSORS INTO COMPOSITES

Fiber optic sensors intended to measure strain fields have been placed into composite parts since the 1980s [1-6]. Figure 1 shows a carbon epoxy coupon which had single mode optical fiber integrated into it with strain measurements supported by a Sagnac interferometer operating closed loop. These tests were performed in the 1985 time frame and were among the first tests conducted using fiber strain sensors to monitor strain fields interior to a composite. In these very early tests the fiber was coated with an epoxy acrylate jacket and when the coupon was subject to tension and compression the response was not uniform due to the optical fiber slipping in the jacketing material.



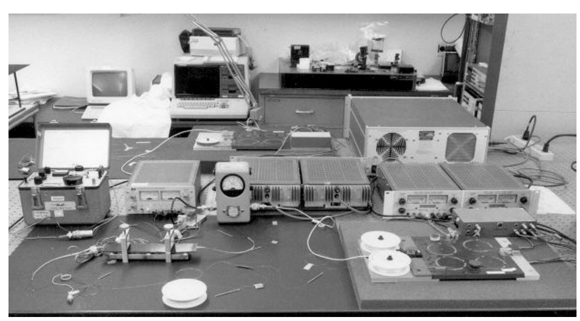


Figure 1. Carbon epoxy composite with embedded fiber optic strain sensors and the Sagnac interferometer strain sensors used to perform strain measurements in 1985.

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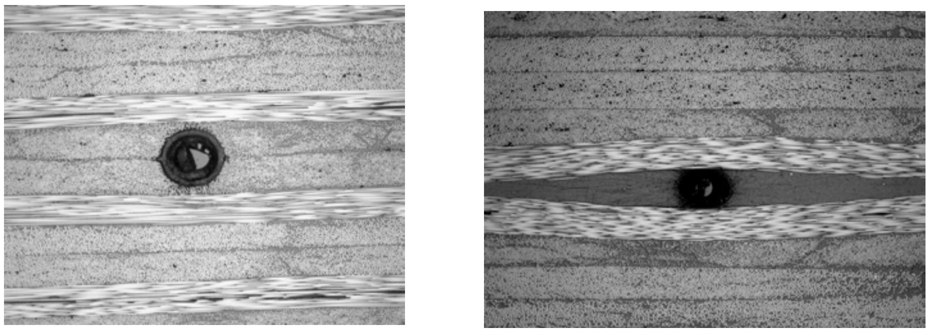
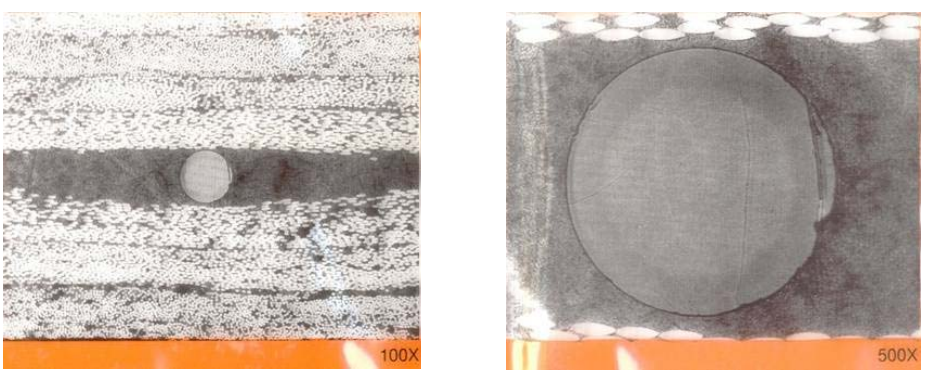
Figure 2 shows a cross section of optical fibers with epoxy acrylate coatings placed parallel and perpendicular to the strength members in the carbon epoxy composite. When the fiber with a diameter of 125 microns is oriented in parallel to the carbon strength members, which are approximately 7 microns in diameter, there is uniform consolidation around the optical fiber. In the case where the fiber is oriented perpendicular to the strength members a characteristic resin "eye" pattern results. This resin "eye" pattern was of considerable concern early on as a possible defect center in the composite part that could lead to premature failure in the form of a delamination. However, testing conducted at a number of labs worldwide concluded that this was not a serious issue unless the fibers were very closely spaced, and even in that case decreasing the overall diameter of the optical fiber could be reduced so that effects were minimized and no loss of strength of the composite could be detected.



(a) (b)

Figure 2. An optical fiber with an epoxy acrylate jacket is placed in a carbon epoxy coupon (a) parallel and (b) perpendicular to the carbon strength members.

To overcome the issue associated with slippage of the optical fiber within the composite material, early efforts involved stripping the coating so that a bare optical fiber was used and the fiber was in direct contact with the resin. This method worked well provided the fiber was stripped cleanly without mechanical damage and the stripped fiber was placed into the composite part quickly to minimize damage associated with water or handling. A better solution that was developed later involved utilizing optical fiber that has been coated with polyimide material that has properties very similar to that found in resins associated with a variety of organic composite materials. In this case, the optical fibers are consolidated so strain is transferred readily from the surrounding composite in a consistent and accurate manner and because the fiber is coated, damage due to handling and storage is minimized. Figure 3 illustrates the cross section of a polyimide coated optical fiber placed in a composite part. The interface is very clean between the coating and the resin material associated with the composite. In general, when dealing with organic composite parts it is necessary to consider the chemistry of the coating material relative to that of the resin associated with the composite.



(a) (b)

Figure 3. Views of an optical fiber coated with polyimide and placed into a thermoplastic composite part with (a) 100x and (b) 500x magnification.

It is also possible to place optical fibers into metallic parts successfully. Lower temperature metals such as aluminum have been used to coat materials and for cast sensors incorporating fiber sensors. The aluminum and optical fibers are highly compatible and uncoated optical fiber may be used during the processing. For higher temperature composites, such as those formed using titanium, the processing temperature of 1000 degrees C and pressures exceeding 7 MPa cause the titanium to be highly reactive resulting in the partial destruction of the optical fibers. By coating the optical fiber with aluminum, a TiAl barrier results that isolates the optical fiber and the result is that intact optical fibers are possible. Similar results may be achieved using different metals such as gold for the coating material. Figure 4 shows an optical fiber that has been successfully embedded into a titanium composite part.

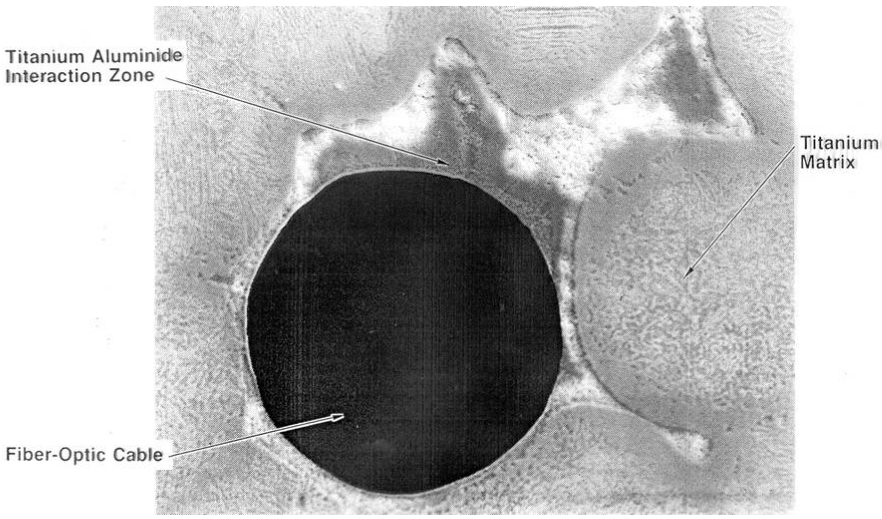


Figure 4. Optical fiber embedded into a titanium composite part

The basic approach is that when fiber optic sensors are embedded into metallic composite parts it is highly important to understand the metallurgy involved insuring optimum results.

The response of the fiber optic sensor to strain in the composite part depends upon its placement and orientation [7-11]. The hardness and density of the strength members and the orientation of the strength members' relative to the sensing fiber can affect the strain transferred to the optical fiber. The thickness of the coating around the fiber, its hardness and matching to the surrounding resin as well as the thickness of the resin rich areas and the properties of the resin itself will also affect strain transfer. A great deal of work in this area remains to be done, however it is possible to obtain signatures of strain values interior to composite materials that are unavailable using other techniques.

It is even possible to measure transverse strain field changes over sub-millimeter lengths of a fiber grating strain sensor. This can be done by using a light source modulated at high speed in combination with interferometeric techniques or, as is shown by the following example, by converting spectral information into localized strain information. These early results are likely to be greatly improved upon in the future but indicate the potential value of this approach.

By matching the spectral profiles of the output of fiber gratings placed in complex composite parts it is possible to assess interior strain fields. Figure 5 illustrates a computer model that is based on a genetic algorithm procedure. The fiber grating is divided into segments and an initial selection of a matching profile is made. The system then calculates the profile and makes a comparison with the actual profile and then iterates toward a solution that closely approximates the actual profile. Figure 5 shows an example of an actual profile and the genetic algorithm solution after one generation and after 200.

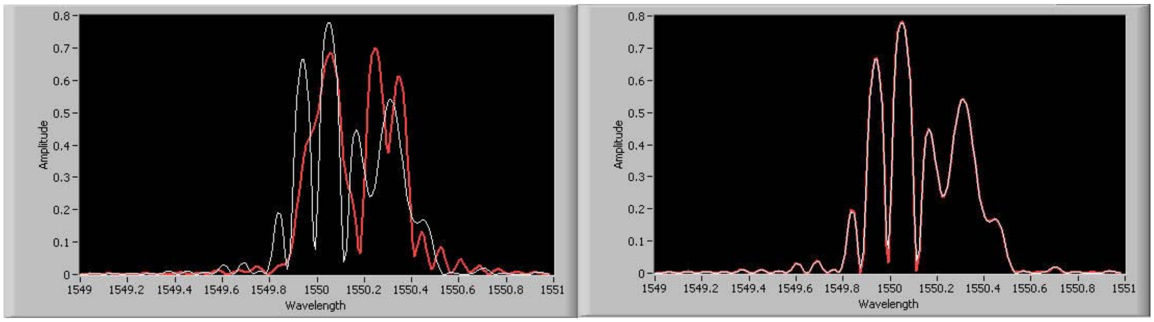


Figure 5. Plots illustrating genetic algorithm fits to generated test data after one generation (left plot) and after 200 generations (right plot). Generated test data is shown in white and genetic algorithm fit in red.

As an example of the power of this method, Figure 6 shows two composite bi-axial weave structures with a width of approximately 4 mm and 2 mm respectively. These fabrics were in turn used to form composite parts with integrated multi-axis fiber grating strain sensors. The resulting profiles that were matched using the genetic algorithm approach are shown in Figure 7, and the resultant calculated output strain along the fiber grating is shown in Figure 8. It is clear from Figure 8 that the woven structure strain period is replicated in a variation of the strain field along the length of the fiber grating.

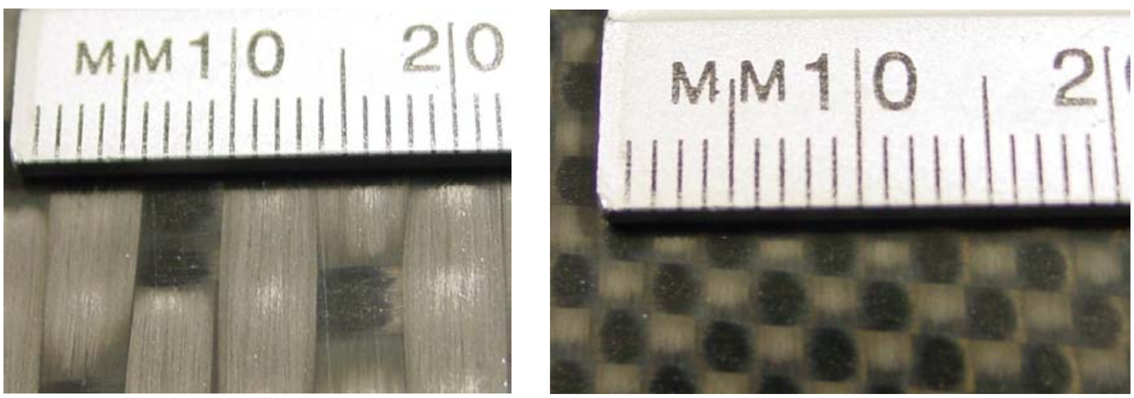


Figure 6. Photographs of coarse and fine weave carbon fiber/epoxy composite panels. The coarse weave panel, with 4mm tow bundle size, is shown on the left and the fine weave panel, with 2mm tow bundle size, is shown on the right.

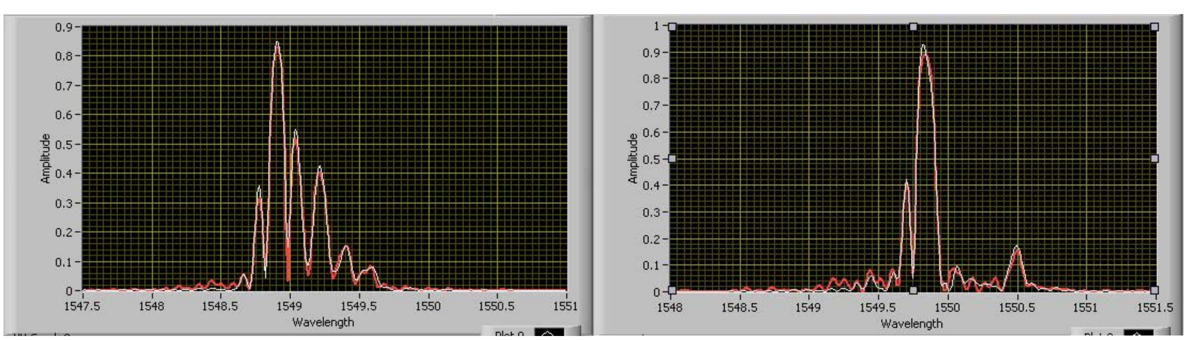


Figure 7. Measured reflection profiles in white and genetic algorithm fits in red for both the coarse weave composite panel (left plot) and the fine weave composite panel (right plot).

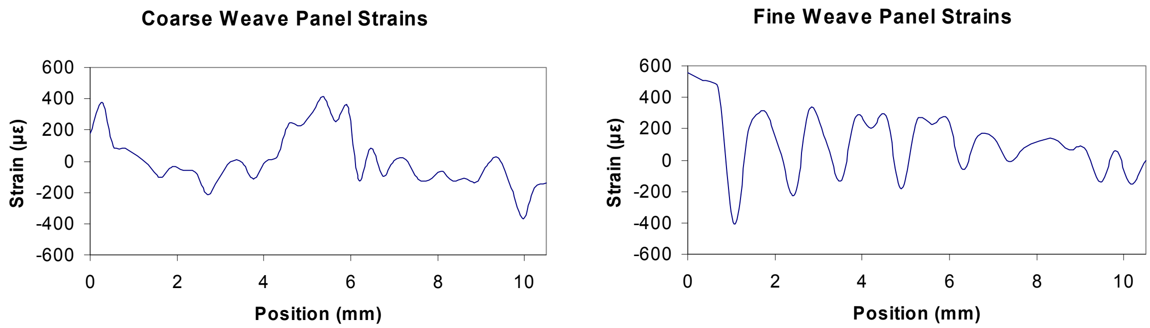


Figure 8. Output plots from genetic algorithm of strain profile as a function of position for both coarse and fine weave panels. The spacing of the major peaks in the strain profiles are similar to the size of the tow bundles in the composite panels.

2.0 PACKAGING AND INGRESS/EGRESS ISSUES

One of the most common modes of failure of fiber optic sensors supporting composite parts involves ingress/egress. Without adequate strain relief a fiber exiting from a cured composite part faces a point of strain concentration at the exit point. A number of methods have been adopted that can be used to reduce these effects. In the coupon associated with Figure 1, a soft silicone gel was used in combination with Teflon tape to form a buffer of the fiber near its exit point.

Later in association with composite cylinders, Teflon tubes were slipped over the fiber and inserted into the part, usually about 2 cm [12]. By capping the end of the tube with silicon gel, air was trapped in the tube and resin was prevented from flowing down the optical fiber. Figure 9 shows this type of installation for two composite cylinders.

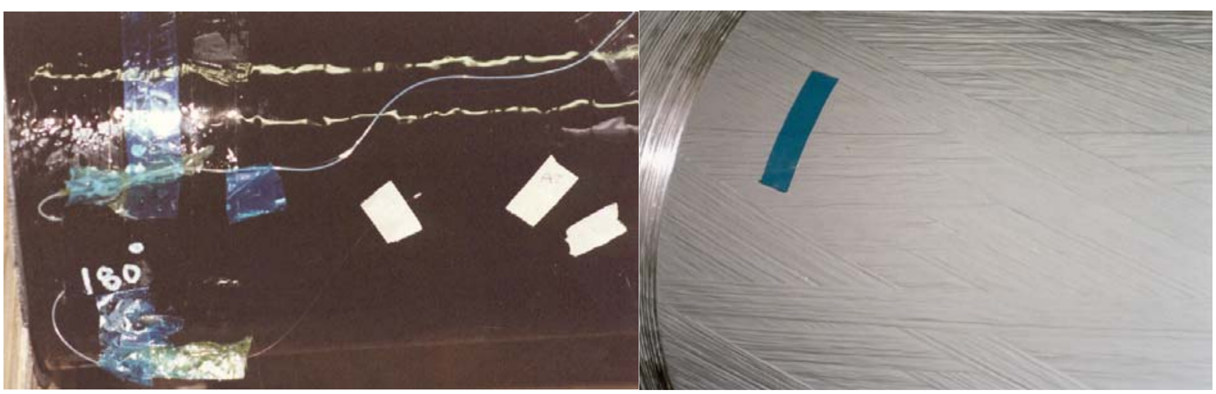


Figure 9. Installation of Teflon tubes into composite parts can be used to provide strain relief at the point of ingress/egress

Figure 10. Installation of fiber grating strain sensors, pre-strained in a tube and placed into concrete and the composite over wrap of a bridge beam.

For large composite installations it may be possible to integrate cabled fiber directly into the composite material. This was done to support an installation of 28 fiber grating strain sensors onto the Horsetail Falls Bridge [13] in the Colombia River Gorge of Oregon. Figure 10 shows the sensors being installed in 1998. Although two of the sensors were lost during construction, the other 26 fiber grating sensors continue to operate without failure. In general, once fiber grating strain sensors are installed into a composite part, failure if it occurs is almost invariably outside of the part at the point of ingress/egress or somewhere in the fiber cabling/connectors outside the composite part. The exception to this is when the composite part itself is subject to catastrophic failure, although there have been many experimental cases when the part fails completely and the fiber sensor survives as it is the strongest component of the composite. An example of this is shown in Figure 11 where 2.5 cm thick composite parts were fabricated with integrated sensors and subject to testing until failure. In some cases even when the part was completely broken the fiber grating strain sensor survived with the optical fiber in the center of the part being the only item connecting the two halves of the part

To avoid problems with strain relief it is possible to build connectors directly into the composite part. One of the first efforts to do so involved a bridge bearing part [14] that was designed to measure transverse and shear strain between a bridge deck and piling.

This system, which is shown in Figure 12, was subject to 300,000 lb loading tests and a similar panel with an integrated connector was subject to repeated strikes by a 20 kg chisel point from heights of up to 3 meters. Fiber grating sensors suffered no measurable damage during these tests; the connectors performed well throughout and only suffered damage when one was directly struck by a rebound of the chisel point. The end of a fiber optic feed through associated with the connector protruding beyond the part was crushed but was readily repaired by using a replacement part.

Figure 11. Integration and test of fiber grating sensors into a 2.5 cm thick composite part subject to break testing under 15,000 kg loads

Figure 12. Composite panel used to measure shear and transverse strain in a composite bridge bearing with integrated connectors

3.0 SUMMARY

Fiber optic sensors may be integrated into a wide range of composite materials successfully by carefully matching coating properties to those of the composite material. Ingress/egress associated with the optical fiber is a critical area that must be addressed. Methods based on strain relief in these areas have been used on a variety of applications. Integrating connectors directly into critical parts holds great promise as an effective means of addressing this issue.

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REFERENCES

1. E. Udd et al., "Fiber-Optic Sensor Systems for Aerospace Applications," Proceedings of SPIE, Vol. 838, p. 162, 1987.

2. E. Udd, "Overview of Fiber Optic Applications to Smart Structures," Review of Progress in Quantitative NDE, Edited by Thompson and Chimenti, Vol. 7A, Plenum Press, 1987.

3. E. Udd, "Overview of Fiber Optic Smart Structures for Aerospace Applications," Proceedings of SPIE, Vol. 986, p. 2, 1988.

4. E. Udd, "Applications of the Fiber Optic Sagnac Interferometer," Proceedings of SPIE, Vol. 985, p. 198, 1988.

5. E. Udd, "Embedded Sensors Make Structures "Smart"," Laser Focus, p. 135, May 1988.

6. E. Udd, "Overview of Fiber Optic Applications to Smart Structures," Review of Progress in Quantitative Nondestructive Evaluation," Plenum Press, New York, p. 541, 1988.

7. K. Black, E. Udd, W. Schulz, S. Kreger, M. Kunzler, T. Taylor and R. Lumsden, "Using Multi-Axis Fiber Grating Strain Sensors to Measure Transverse Strain and Transverse Strain Gradients in Composite Materials with Complex Weave Structures", Proceedings of SPIE, Vol. 4694, p. 162, 2002.

8. K. Davol, E. Udd, S. T. Kreger, M. Kunzler and M. Laylor, "Monitoring of Advanced Composite Weave Structures Using Multi-axis Fiber Grating Strain Sensors", Proceedings of SPIE, Vol. 5278, p. 128, 2003.
9. E. Udd, D. V. Nelson, C. M. Lawrence and B. A. Ferguson, "Three Axis Strain Plus Temperature Fiber Grating Sensor", Proceeding of SPIE, Vol. 2718, 1996.
C.M. Lawrence, D.V. Nelson, E. Udd, "Multiparameter sensing with fiber Bragg gratings", Proc. SPIE Vol. 2872, p. 24, 1996.

10. E. Udd, "Advanced strain measurement applications of fiber optic grating sensors", Proc. SPIE Vol. 2872, p. 18, 1996.

11. E. Udd, D.V. Nelson, C.M. Lawrence, B.A. Ferguson, "Three-axis strain and temperature fiber optic grating sensor", Proc. SPIE Vol. 2718, p. 104, 1996

12. E. Udd, K. Corona, K. T. Slattery and D. J. Dorr, "Fiber Grating System Used to Measure Strain in a 22-Foot Composite Utility Pole", Proceedings of SPIE, Vol. 2721, 1996.

13. J. Seim, E. Udd, W. Schulz, H.M. Laylor, "Composite Strengthening and Instrumentation of the Horsetail Falls Bridge with Long Gauge Length Fiber Bragg Grating Strain Sensors", SPIE Proceedings, Vol. 3746, p. 196, 1999.

14. E. Udd, W.L. Schulz, J. Seim, K. Corona-Bittick, J. Dorr, K.T. Slattery, H.M. Laylor, G.E. McGill, S.B. Chase, "Fiber Optic Smart Bearing Load Structure", SPIE Proceedings, Vol. 3587, p. 40, 1999.